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Improving Students' Visual Representation and Conceptual Understanding to Overcome Learning Difficulties in Geometry

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Abstract
This study investigates the impact of using GeoGebra, a dynamic geometry software, in enhancing students' visual representation and conceptual understanding of Geometry, mainly focusing on vector concepts. The study involved 168 10th -grade students in Phnom Penh, Cambodia. The research used a quasi-experimental design with control and experimental groups. The experimental group received instruction with GeoGebra, while the control group followed traditional methods. Data from pre- and post-tests were analysed using descriptive statistics, Mann-Whitney U tests, and N-Gain scores. The results showed that the GeoGebra group had significantly higher N-Gain scores, indicating improved comprehension and problem-solving skills. The study suggests integrating dynamic GeoGebra software into the curriculum to provide a more interactive learning experience and improve learning in Geometry.

Keywords: Conceptual Understanding, GeoGebra, Geometry, Visual Representation, Vector Operations.

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INTRODUCTION

Many students and teachers find geometry complex to teach and learn through visualisation, respectively, which can lead to intricate conceptual understanding (CU). Students' difficulty with visualisation can be a challenge when solving geometry problems and can lead to poor CU. Many scholars have found that students struggle to solve geometry problems because the geometrical concepts are abstract and require spatial reasoning (Clements et al., 1992; Lowrie, Logan, & Hegarty, 2019). Visualisation allows learners to see the relationships and properties of shapes, and to enhance their understanding of problems (Al-Mutawah et al., 2019; Perry & Len-Ríos, 2019; Samphantakul & Thinwiangthong, 2019).

The difficulties to visualise that students encounter are of three main aspects: visual perception, visual-spatial, and visual representation (VR). For example, in solving a geometric problem, students might first identify the geometric shape by using visual perception, then manipulate these shapes mentally by applying visual-spatial skills, and finally draw diagrams or graphs that aid in solving the problem using VR. All three were implemented in different educational stages. In primary education, the focus is on visual perception, leading to the development of visual-spatial skills in lower secondary one.

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Finally, upper secondary education emphasises VR. Students' Understanding the integration of visualisation within the context of geometry can improve their learning outcomes, and foster a deep CU of geometric concepts (Khalil et al., 2024; Majeed & ALRikabi, 2022; Porat & Ceobanu, 2024).

While this study focuses on the upper secondary level, VR and CU are the focal unit of analysis. However, the test items may include some visual perception and visual-spatial. Even though they are not directly addressed, they are interrelated and embedded in the VR. Therefore, to overcome learning difficulties in Geometry, the improvement of VR and CU are needed.

On the other hand, to overcome learning difficulties, there are many approaches in improving students' VR and CU, such as improving teacher knowledge in geometry, developing effective teaching and learning materials, choosing the appropriate teaching methods, using dynamic geometry software (DGS), encouraging students to learn geometry, and promoting students' reflection for problem thinking. Among these, utilising DGS, namely GeoGebra, which various scholars recommended, is one significant approach to help students improve their Geometry problem-solving abilities on VR and CU (Azizah et al., 2021; Hohenwarter et al., 2009; Kholid, 2022; Siswanto et al., 2024).

GeoGebra particularly is an interactive mathematics software that has gained global attention from researchers and educators for its capabilities in visualising, exploring, and proving mathematical concepts. It combines various mathematical tools, including graphics, geometry, algebra, calculus, and statistics into a dynamic and user-friendly platform. GeoGebra enables students to visualise mathematical concepts concretely through dynamic geometrical representations. It is a free open-source software and is available both online and offline (Bekene Bedada & Machaba, 2022; Zhang et al., 2023; Zulnaidi & Zamri, 2020). Therefore, GeoGebra was selected in this study as an experimental tool in investigating whether it can help improving students' VR and CU to overcome learning difficulties in Geometry.

However, there is a lack of research about the effectiveness of using GeoGebra in teaching and learning Mathematics, particularly Geometry, in Cambodia education context. At the same time, the students faced difficulties in solving Geometry problems. According to the National Learning Assessment (NLA) of November 2021 (MoEYS, 2023), students' achievement in mathematics remained low compared to the NLA of 2016, which the average score in general was only 38%. The lowest average achievement was in the Geometry domain, among others (Algebra, statistics, Measurement, and Numbers), with only 35% of sixth graders and 46% of eighth graders students completing the NLA (test) correctly (Bhatta et al., 2022; MoEYS, 2023). Similarly, the 12th grade national examination report in the academic year of 2020–2021 showed that only 47.93% of students could solve Geometry problems correctly, specifically vector content (Bhatta et al., 2022; MoEYS, 2022, 2023).

Therefore, vector contents was identified as students' difficulty with VR and CU in solving Geometry problems. GeoGebra software is a potential tool for improving the ability of upper-secondary students to overcome challenges. Thus, in this study vector content was chosen for constructing the teaching practice and developing test items to measure the improvement of students' VR and CU. There are two reasons for choosing the vector topic: (1) vector forms the foundation concept of Geometry, which relates to many high difficulty level topics in mathematics, such as linear algebra, physics, engineering, and navigation for upper secondary students. Students need to grasp vectors contents in understanding more complex concepts in their studies (Dray &

Manogue, 2023; Wrede, 2013); (2) vector is a foundation topic addressed in Cambodia's 10th grade of the upper secondary school mathematics curriculum and textbooks in Cambodia. Students who understand vector concepts can help them understand other related topics more quickly (MoEYS, 2018a, 2018b, 2020a).

The discussion above clarifies that students having poor understanding of VR can have poor CU (Duval, 1999). While this study mainly focuses on upper secondary education, VR and CU are the focal targets, the test items may include visual perception and visual-spatial. Even though these are not directly addressed, they are implicitly considered because they are interrelated. Hence, this study considers these two through the analysis of test items because they are embedded in the VR.

Therefore, there is a need for more evidence in research on using GeoGebra for teaching and learning Geometry in Cambodia's education context. In this sense, the current study aims to measure the improvement of students' VR and CU to overcome learning difficulties in Geometry using GeoGebra software in upper secondary schools in Cambodia, focusing on vector concepts.

In adapting to the previous studies and because of the measurement purpose, VR refers to students' ability to create geometrical drawings to clarify the problem and skills in performing picture representations, including visual, symbolic, and verbal presentations. CU refers to students' ability to grasp mathematical concepts and perform a correct mathematical procedure related to VR. Two main questions have been set for this study:

1. What are the students' difficulties in learning Geometry through visualisation?
2. To what extent does GeoGebra software improve students' VR and CU to overcome learning difficulties in Geometry for Cambodia upper secondary schools?

The findings of this study will contribute to the development of dynamic geometry software, particularly GeoGebra. This software help to improve students' mathematical abilities and respond to the need for instructional strategy to support them in overcoming specific learning difficulties in Geometry.

RESEARCH METHOD

Research Design

The study employed a quasi-experimental, non-equivalent group research design with a control and experimental group, pre- and post-tests. This design allows the researcher not to assign participants randomly. It also allows the researcher to recognize a comparison group that is comparable to the experimental group in terms of pre-intervention characteristics (Creswell & Creswell, 2018; Gay et al., 2012). The study was designed to compare the impact of using GeoGebra on students' VR and CU of geometry, explicitly focusing on vector and vector operation content, to that of instruction without utilising GeoGebra.

Participants

The study involved 10th grade high school students from two schools in Phnom Penh, the capital city of Cambodia, called School A and School B, during the 2022-2023 academic year. Two classes were chosen from each school, one assigned as the experimental group and the other as the control group. The experimental group received GeoGebra instruction, while the control group received the traditional teaching method. Quasi-random sampling was used with approval from the school principals, emphasising ethical considerations and cooperation. All available students from the selected schools were invited to take part in the test. It is important to note that the selection process and class assignment was determined by the school principals. It was not proposed to create a representative sample of the Cambodian high school student population. They all received the same curriculum covering vector and vector operations for upper secondary education. In total, 168 (103 females) high school students participated in the test, of which 100 is for the experimental group and 68 for the control group.

Instrument

The researcher developed the experimental lessons before the teaching practice period. There were five weeks to implement the teaching practice. The experimental group used GeoGebra software as an experimental lesson covering vector and vector operation contents, and the control group was taught as traditional, using the same content but without GeoGebra software. Pre-and post-tests were administered to control and experimental groups alike.

The construction of test items was adapted to contents and sub-contents of vector and vector operation concepts, which existed in the textbook published in 2020 (MoEYS, 2020a) and the Cambodian Mathematics Curriculum for upper secondary school published in 2018 (MoEYS, 2018a, 2018b), distributed by Ministry of Education Youth and Sports (MoEYS) of Cambodia. The test items consist of five open-ended questions extracted from three sub-contents: (1) 'Meaning of a Vector', (2) 'Addition and Subtraction of Vectors', and (3) 'Component of a Vector in a Plane'. The five test items included VR and CU concepts.

The test items were piloted twice before being distributed to the respondent students to complete the test. Three experts validated the test items: two were teachers familiar with vector concepts from their experiences teaching 10th grade, and another expert, teacher educator from the National Institute of Education (NIE) of Cambodia majoring in mathematics. The validation process involved these experts reviewing the test items to ensure they were clear, relevant, aligned with the curriculum and textbook and to meet the current context. The reliability of the first pilot test items, measured by Cronbach Alpha, was 0.786; however, the allotted one hour (fifty minutes in teaching hour) needed to be increased for the students to complete all the problems. The test items were revised. Test item 1 was split into two because it originally contained two distinct questions. Test item 5 was deleted because its content was beyond the scope of 10th grade students.

The second pilot was conducted to confirm if the revised time limit was acceptable. The reliability score, confirmed with a Cronbach's Alpha of 0.904, indicated that the duration of 50 minutes was suitable for completing all test items, and it confirmed that the test items could be measured. The table of finalized test items were arranged by each sub-content is shown below.

Table 1. Finalized test items arranged by sub-contents

Sub-Content	Test Items of VR	Test Items of CU
Meaning of Vector	1, 2	1, 2
Addition and Subtraction of Vector	3, 4	3, 4
Component of a Vector in a Plane	5	5
Total number of test items	5	5

Source. The researcher developed by adapting the Cambodia textbook in 10^{th} grade (MoEYS, 2020b)

Table 1 shows test items 1 and 2 were covered by the sub-content of the Meaning of Vector; test items 3 and 4 were covered by the sub-content of Addition and Subtraction of Vectors; and test item 5 was dealt with the sub-content of 'Component of a Vector in a Plane'. Each test item was constructed to measure students' difficulties with VRs and CU in learning vector concepts concurrently.

Data Analysis

A scoring rubric was developed, and the student responses were marked after consulting with experts and peer review to analyse the results. The rubric was categorised as 'No response', where there is no attempt to answer the question, marked as '0'; 'Incorrect', where the answer provided is completely wrong, marked as '1'; 'Partly correct', where the answer shows some understanding of the concept but is incomplete or contains minor errors, marked as '2'; and 'Correct', where the answer is completely correct and demonstrates a clear understanding of the concept, mark as '3'. The total scores of correct of five test items were marked 30, of which 15 is for VR and another 15 for CU.

The data analysis drew from student responses following a scoring rubric. IBM SPSS Statistics Data Editor version 27 was used to analyse the data, which was carried out to describe the students' abilities in solving vector problems related to VR and CU. It was accomplished by determining descriptive statistics, namely the measurement of central tendency and the size of data distribution.

We investigated the intervention of vector and vector operation content that both groups did not learn as an intervention lesson alike to determine if one group had learned this material before the other to ensure equivalence between the groups Because the participants were not randomly selected.

However, both groups started this content simultaneously from the beginning of teaching practice. Furthermore, the difference between the mean scores in students' VR and CU was compared using the Mann-Whitney U Test nonparametric because the two data groups were not normally distributed (Morgan et al., 2011). This analysis evaluated the strength of the relationship (effect size) followed Cohen (1988). Although an effect size measure is not provided in the output, it is easy to compute an from information provided in the test statistic table using the conversion formula

The comparison of effect size were classified as much larger if ≥|.70|, large if |.50| ≤ <|.70|, medium if |.30| ≤ <50, and small if <|.30|(Morgan et al., 2011).

However, the distribution of the data of the experimental group and control group was statistically significantly different from the pre-test result. Thus, to measure the difference between the improvement of both groups, we calculated the average normalised gain score (N-Gain score), as defined by Hake (1998), to assess the student's improvement after teaching practice. This measure offers more insight than a simple difference by calculating the fraction of concepts learned that were not already known at the start of the intervention lesson. To put it in another way, it is the difference between the total score and the average score of the pre-test (or maximum possible gain) as the below formula:

Ideal Score - Pretest Score

The gain value is used to quantify how much the learners have improved relative to the maximum possible improvement they could have achieved. The percentage of N-Gain scores categorised as less than 40% was indicated as not effective; between 40% and 55% was indicated as less effective; between 56% and 75% was indicated as effective enough, and greater than 76% was indicated as effective (Hake, 1998).

RESULTS AND DISCUSSION

Result

Through the analysis of the student's responses, the result obtained as below.

Students' difficulty in learning Geometry through VR and CU

The result of students' responses to test items for VR and CU covering vector and vector operation contents, in general, can be indicated by their response obtained after taking the test with a correct answer, along with the scoring rubric. The descriptive statistical analysis is shown in Table 2.

Table 2. The descriptive statistics of students' responses through pre-test and post-test

Descriptive Statistics							
	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	
	Statistic	Statistic	Statistic	Statistic	Statistic	Statistic	Std. Error
pre-test of VR	168	1	10	4.60	1.946	0.422	0.187
pre-test of CU	168	0	11	2.92	2.430	0.591	0.187
post-test of VR	168	3	15	10.41	2.450	-0.448	0.187
post-test of CU	168	0	15	10.45	3.764	-0.712	0.187
Valid N (listwise)	168						

Table 2 illustrates that the average score of students' abilities to solve vector and vector operation contents on VR is better than CU for the pre-test. In the VR, the average score of students who solved the problem was 4.60, while in CU, the result was 2.92. Here, the ability of students to solve problems related to vector concepts depends on their knowledge of VR. This result means that the ability of students to solve the problem in VR format is easier because they only demonstrate the shape derived from the problem given, unlike the procedure of vector calculation, such as addition and subtraction of vector contents, which are often difficult to understand and need special treatment so that students understand well.

In contrast, in the post-test, the average score of students' abilities to solve the problem on CU is better than on VR for the post-test. In CU, the average score of students who solved the problem was 10.45, while in VR, the result was 10.41. However, the students' abilities to solve vector concept problems related to VR and CU are almost similar because they are interrelated.

On the other hand, the percentage of the students' who are able to solve each test item related to VR and CU correctly was obtained from their responses on the post-test results. The percentage of post-test results is shown in Figure 1 below.

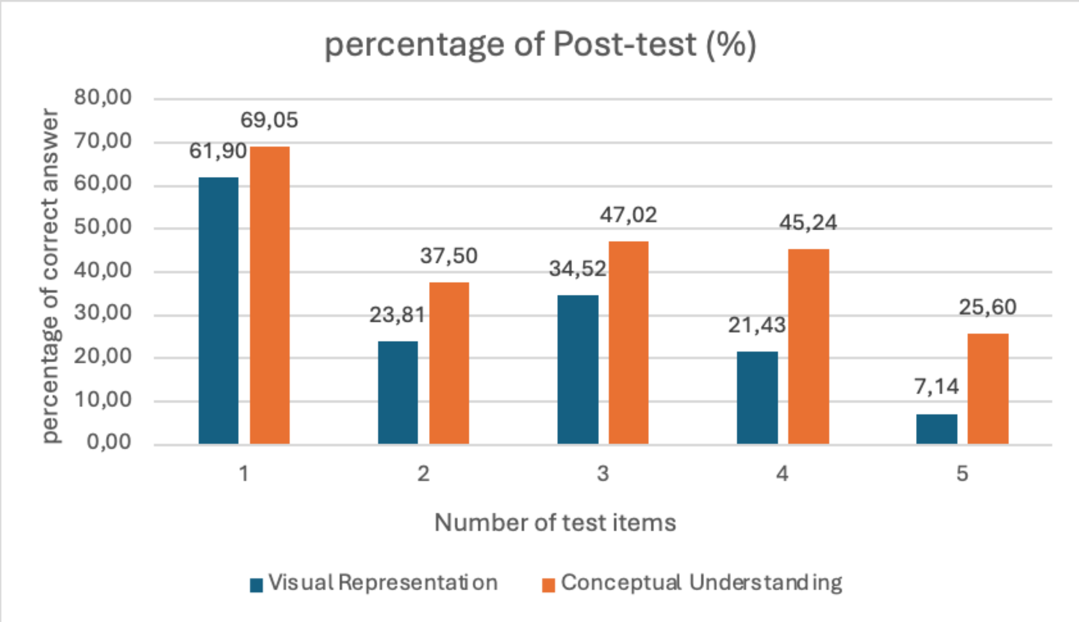

Figure 1. Percentage of students who responded correctly on VR and CU

Figure 1 shows that the percentage of students who answered correctly on test items assessing CU was higher than VR, respectively. However, this difference varied depending on the context of the problem. The highest significant difference was perceived in test item 4, where the percentage of correct responses for CU was 23.81%. On the other hand, in test item 1, students who answered the test item correctly assessing CU were almost similar to those in VR. The significant difference between test item 1 is 7.14%.

However, based on students' calculating procedures, they encountered difficulties in interpreting VRs. These difficulties included an inability to create geometrical drawings to clarify the given problem and a lack of skills in performing picture representations, including visual, symbolic and calculation procedures. Similarly, the students faced difficulties in CU due to an inability to grasp mathematical concepts and perform correct mathematical procedures related to VR, which tends to lead to low achievement in solving Geometry problems, particularly vector and vector operation concepts.

Therefore, in analysing students' responses, we found that their difficulties in solving vector and vector operation problems through VR and CU were below the medium level for all test items except for item 1 (See Figure 1). The result suggests that a lack of VR and CU may contribute to low performance in solving geometry problems.

Student's improvement in solving vector concepts differs between VR and CU

The Mann-Whitney U Test was used to compare the test score improvement between the experimental group and the control group. This comparison is based on students' scores on CU and VR of vector and vector operations. The results of this comparison are presented in Table 3.

Table 3. The comparison of the test scores improvement of pre-test and post-test

			Ranks				
	Group	**N**	**Mean Rank**	**U**	**Z**	**r**	**Sig**
Pre-test	Experimental Group	100	99.61	1889	-4.9	-0.38	p<.001
	Control Group	68	62.28				
	Total	168					
Post-test	Experimental Group	100	100.72	1778.5	-5.251	-0.41	p<.001
	Control Group	68	60.65				
	Total	168					

Table 3 indicates that the experimental group of 100 students had significantly higher mean ranks of 99.61 compared to that of 62.26 of the 68 students in the control group on the pre-test for both VR and CU, which U=1889, p<.001, z=-4.90, and r=-0.38. According to Cohen (1988), this represents a medium to large effect size. Similarly, a significant difference was found in the mean ranks between the experimental and the control group on the post-test result for both VR and CU, where U=1778.50, z=-5.251, p<.001, and r=-0.41, which indicates medium to large affect size, (Cohen, 1988).

Furthermore, to measure the effective of pre- and post-teaching practice using GeoGebra and without using GeoGebra, the N-Gain score test was intentionally used. The N-Gain score test is applicable when there is a significant difference between the average post-test value of the experimental group and

the post-test value of the control group. The result of the N-Gain score is shown in Table 4.

Table 4. Normalised Gain score percentage (%)

			Descriptive				
Experimental group		**Statistic**	**Std. Error**	**Control group**		**Statistic**	**Std. Error**
Mean		67.3397	1.66002	Mean		50.6506	2.92059
95% Confidence Interval for Mean	Lower Bound	64.0458		95% Confidence Interval for Mean	Lower Bound	44.8211	
	Upper Bound	70.6335			Upper Bound	56.4801	
5% Trimmed Mean		67.8638		5% Trimmed Mean		50.4030	
Median		67.9286		Median		46.4286	
Variance		275.568		Variance		580.029	
Std. Deviation		16.60023		Std. Deviation		24.08378	
Minimum		15.00		Minimum		0.00	
Maximum		100.00		Maximum		100.00	

Range	85.00		Range	100.00	
Interquartile Range	23.92		Interquartile Range	41.58	
Skewness	-0.532	0.241	Skewness	0.208	0.291
Kurtosis	0.591	0.478	Kurtosis	-0.946	0.574

Table 4 shows that the average value of the N-Gain score for the experimental group is 67.34%, which is categorised as effective enough with a minimum N-Gain score of 15% and a maximum of 100%. Meanwhile, the average N-Gain score for the control group is 50.65%, which is categorised as less effective, with a minimum N-Gain score of 0% and a maximum of 100%.

Therefore, it can be concluded that the use of GeoGebra is effective enough in improving students' VR and CU to overcome learning difficulties in solving Geometry, particularly vector and vector operation.

Discussion

Improving students' VR and CU is crucial for learning and solving Geometry problems. The result of test items show that students could not create geometrical drawings to clarify the problem and improve their skills in performing picture representations. These make the students unable to grasp mathematical concepts and perform correct mathematics procedures.

Moreover, visual perception and visual-spatial skills are essential in relation to VR and CU in solving Geometry problems for fostering deep understanding, more effective teaching techniques, better learning success, and a deeper understanding of the subject, coherent learning progression and trajectory, which can improve students develop a CU (Gal & Linchevski, 2010; Jones & Tzekaki, 2016b; Khalil et al., 2024; Lowrie, Logan, Hegarty, et al., 2019; Majeed & ALRikabi, 2022; Porat & Ceobanu, 2024). This indicated that students need to build their foundation from lower grades, which is necessary to strengthen CU.

Comparing experimental and control groups, a key finding of this study is the significant difference in the performance of the experimental group, which used GeoGebra, compared to the control group, which did not. The experimental group showed significant improvement in both VR and CU, as evidenced by the higher N-Gain scores. This suggests that GeoGebra is not merely a supplementary tool but a potent instructional aid that can significantly enhance students' comprehension of complex geometric concepts. The medium to large effect sizes further support the software's efficacy in improving students' mathematical abilities, aligning with the findings of Zulnaidi and Zamri (2020), who also reported positive impacts of GeoGebra on students' learning outcomes.

Despite the improvements, the study also highlights persistent challenges that students face in VR and CU. These difficulties were most pronounced in tasks requiring students to translate visual information into mathematical expressions and vice versa. For example, test item 4 requires students to find vector components and test item 1 requires students to plot points accurately on a Cartesian plane; many struggled with correctly identifying and applying the necessary procedures. This is consistent with the findings of Gal and Linchevski (2010), who noted similar challenges among students. This suggests that while tools like GeoGebra can significantly aid learning, there remains a need for targeted instructional strategies to further support students in learning Geometry.

The results of this study have important implications for teaching practices in geometry. First, we suggest that integrating dynamic geometry software like GeoGebra into the curriculum can greatly enhance students' understanding of complex geometric concepts because GeoGebra features and functions are easy for students and teachers to explore more in depth in improving their knowledge and skills. Teachers should consider incorporating such tools into their lessons to provide students with a more interactive and engaging learning experience (Hohenwarter et al., 2009; Zulnaidi & Zamri, 2020). Furthermore, given the persistent challenges in VR and CU, it is crucial for educators to focus on these areas more intensively, possibly through additional exercises and instructional methods that explicitly target these skills.

Additionally, the study points out the importance of developing students' visual-spatial skills from an early stage in their education. As visual perception, visual-spatial reasoning, and VR are interlinked and essential for a solid understanding of geometry, these skills should be nurtured systematically across different educational stages (Jones & Tzekaki, 2016a; Žakelj & Klancar, 2022).

The findings of this study are similar to previous research that has emphasised the importance of visualisation in learning geometry (Elia et al., 2018). For instance, previous studies have shown that students who struggle with visualisation often find it challenging to grasp geometric concepts fully, leading to lower performance in mathematics overall (Despina A & Silver, 2004). The use of GeoGebra, as demonstrated in this study, aligns with other research that supports the integration of dynamic geometry software as a means to improve mathematical understanding and problem-solving abilities (Kholid, 2022). However, this study contributes further by providing specific insights into the Cambodian educational context, where such interventions are narrative and imply results.

While the study provides valuable insights, it also has some limitations that should be addressed in future research. The non-random selection of participants may limit the generalizability of the findings. Future studies could employ a more randomised design to validate these results across a whole country population. Additionally, while the study focused on vector and vector operation concepts, further research could explore the effectiveness of GeoGebra in other areas of geometry and mathematics more broadly. Longitudinal studies could also examine the long-term impact of such interventions on students' mathematical abilities (Creswell & Creswell, 2018).

Therefore, while GeoGebra proved effective in this study, exploring how different teaching methods can be integrated with dynamic geometry software to improve student learning achievement is essential. Future research should investigate how combining various instructional strategies with technology can further enhance students' VR and CU of geometry (Ziatdinov & Valles Jr, 2022).

CONCLUSION

This study highlights the effectiveness of using GeoGebra in enhancing students' visual representation (VR) and conceptual understanding (CU) of geometry, particularly in solving vector-related problems. The findings suggest integrating dynamic geometry software like GeoGebra can effectively improve students' VR and CU. The experimental group, which used GeoGebra, showed a marked improvement in VR and CU compared to the control group, as evidenced by higher N-Gain scores between the pre-test and post-test. This indicates that GeoGebra is not just a supplementary tool but an effective instructional aid that can significantly improve students' understanding of complex geometric concepts. Therefore, this study contributes valuable insights into the potential of dynamic geometry software, particularly GeoGebra, in improving students' mathematical abilities and highlights the need for targeted instructional strategies to support students in overcoming specific learning difficulties in Geometry.

Future research should explore the integration of GeoGebra and other dynamic geometry software across different mathematical domains and educational levels. Additionally, further studies could investigate how combining various instructional strategies with technology can enhance students' learning outcomes in mathematics, particularly in learning Geometry.

DECLARATION

Author Contribution

All authors contribute to the research process, such as collecting the data, analysing the data, and writing the manuscript. All authors approved the final manuscript.

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This research did not receive any funding.

Conflict of Interest

Both authors declare that they have no conflicting interests.

Ethics Declaration

We, as authors, acknowledge that this work has been written based on ethical research that conforms with the university's regulations and that we have obtained permission from the relevant participants to collect data. We support the International Journal on Emerging Mathematics Education (IJEME) in maintaining high standards of personal conduct and practising honesty in all our professional practices and endeavours.

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